North American CO2 Sources

Legend
CO2 Sources

- ● Ethanol Plants
- ● Cement Plants
- ● Ag Processing
- ● Electricity Generation
- ● Fertilizer
- ● Industrial
- ● Petroleum and Natural Gas Processing
- ● Refineries/Chemical
- ● Unclassified

Yearly CO2 Release (Metric Tons)

- · 0 - 250,000
- · 250,001 - 500,000
- · 500,001 - 750,000
- ● 750,001 - 10,000,000
- ● 10,000,001 - 18,000,000
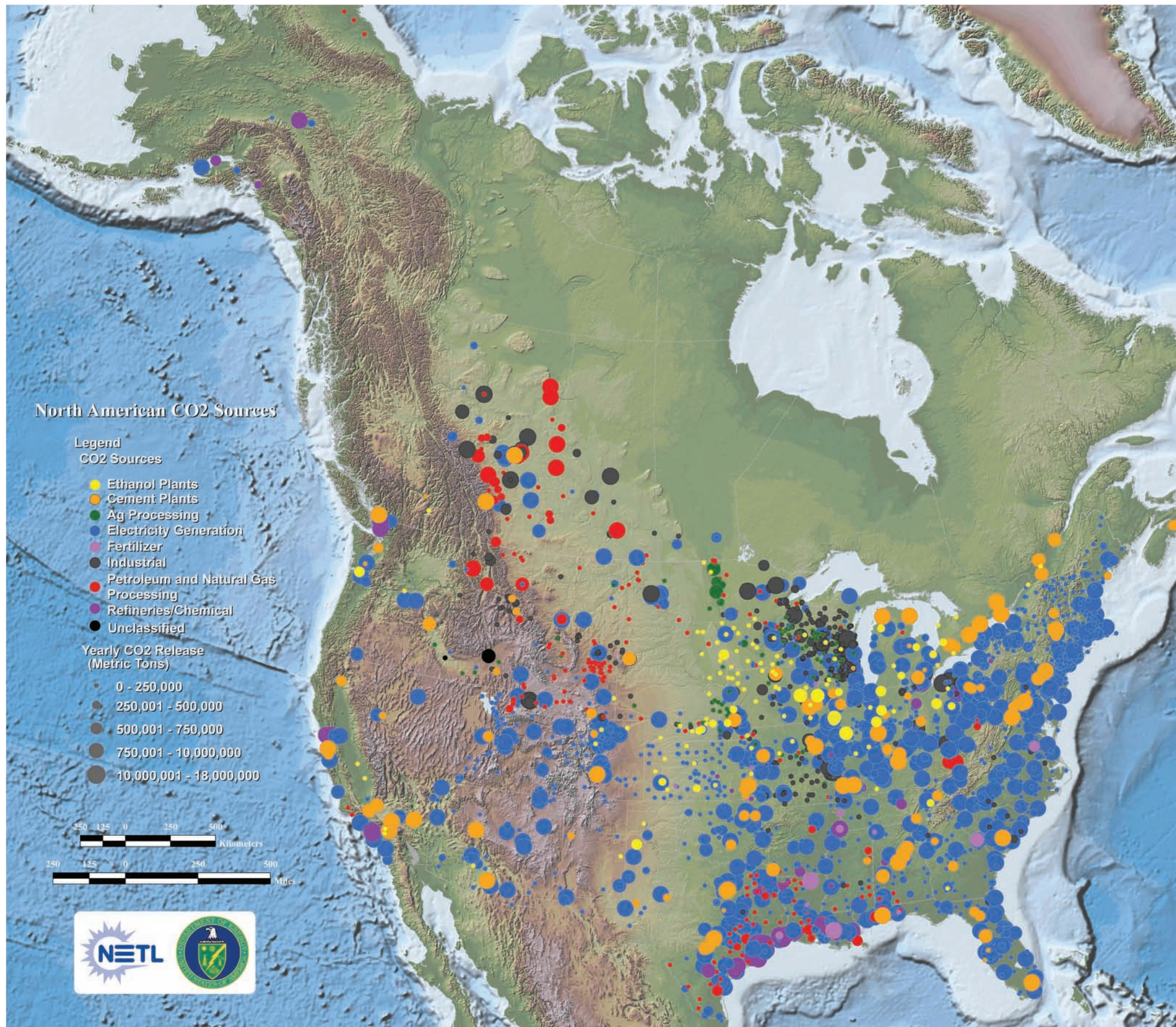
This map displays stationary source data which were obtained from the RCSPs and other external sources and compiled by NATCARB. Each colored dot represents a different type of stationary source with the dot size representing the relative magnitude of the CO_2 released (see map legend).
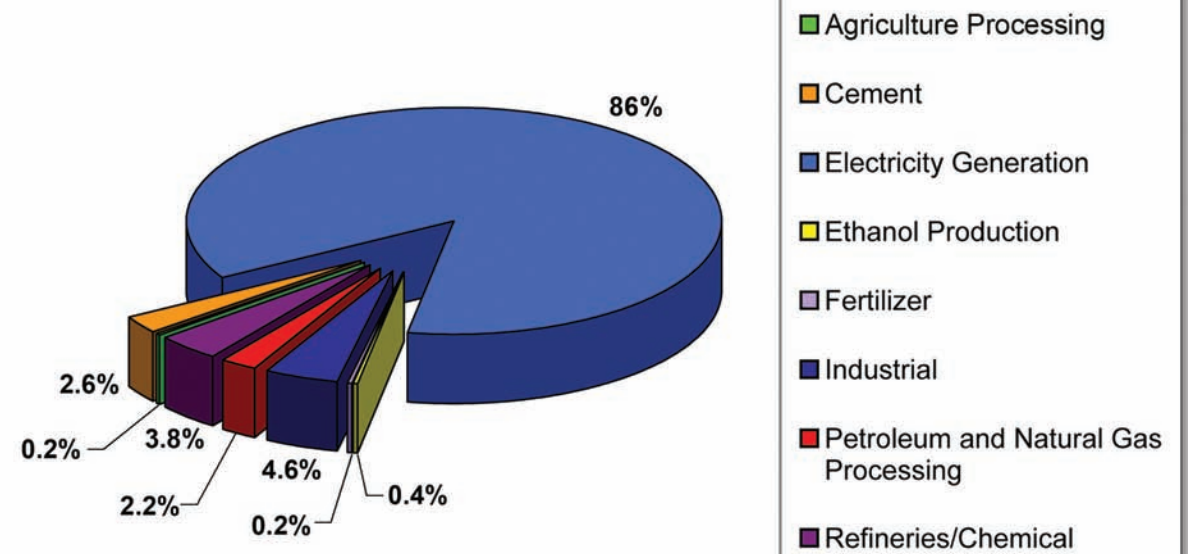
Carbon Dioxide Sources

There are two types of CO_2 emission sources: stationary sources and non-stationary sources. Stationary source emissions come from a particular, identifiable, localized source, such as a power plant. CO_2 from stationary sources can be separated from stack gas emissions and subsequently transported to a geologic sequestration injection site for subsurface storage. The "North American CO_2 Sources" map displays the location and relative magnitude of a variety of CO_2 stationary sources.

Non-stationary source emissions include CO_2 emissions from the transportation sector. The evolving terrestrial sequestration technologies are one way to address these emissions.
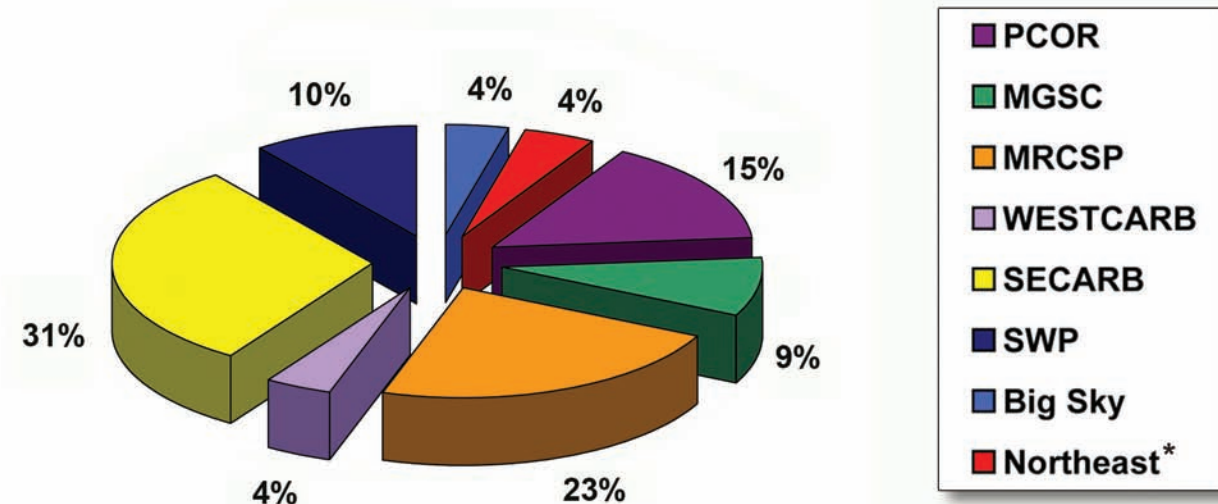
According to the EPA, in 2004, total U.S. GHG emissions were estimated at 7,074.4 million metric tons (7,798 million tons) CO_2 equivalent. This estimate included CO_2 emissions as well as other GHGs such as methane (CH_4), nitrous oxide (N_2O), and hydrofluorocarbons (HFCs).

The "Percentage CO_2 Stationary Source Emissions by Category" pie chart contains values, gathered by the RCSPs and NATCARB (illustrated on the "North American CO_2 Sources" map), showing that CO_2 stationary source emissions result largely from energy use and industrial processes. While not all potential GHG sources have been examined, NETL's RCSPs have documented the location of more than 4,365 stationary sources with total emissions of 3,809 million metric tons of CO_2. The "CO_2 Stationary Source Emission by Partnership" pie chart displays the amount of CO_2 stationary source emissions identified by each RCSP.

Percentage CO₂ Stationary Source Emissions by Category

Legend:
- Agriculture Processing
- Cement
- Electricity Generation
- Ethanol Production
- Fertilizer
- Industrial
- Petroleum and Natural Gas Processing
- Refineries/Chemical

86%, 2.6%, 0.2%, 3.8%, 2.2%, 0.2%, 4.6%, 0.4%

CO₂ Stationary Source Emissions by Partnership (Million Metric Tons)

Legend:
- PCOR
- MGSC
- MRCSP
- WESTCARB
- SECARB
- SWP
- Big Sky
- Northeast*

10%, 4%, 4%, 15%, 9%, 23%, 4%, 31%

* Northeast category includes states not covered by the RCSPs

Capacity Calculations for National Estimates

DOE's NETL, NATCARB, and the RCSPs worked together to establish some common assumptions and methodologies for determining CO_2 capacity estimates for various geologic formations. Results of this collaboration, detailed in the *Methodology for Development of Carbon Sequestration Capacity Estimates* document (available in Appendix A), are presented in this *Atlas*. The methodologies used were designed to integrate results of assessments completed by the seven RCSPs for three types of geologic formations: oil and gas formations, unmineable coal seams, and saline formations. These methodologies were developed to be consistent across North America for a wide range of data. Storage capacity methodologies are still being developed for basalt formations and organic-rich shales.

The approach used included quantification of the storage resources available at a subregional scale and application of an estimate of the efficiency at which these resources can be used for storage of CO_2. Storage efficiency represents a percentage of the storage resources that can be used for storage in all formations throughout the U.S. and Canada. Monte Carlo (statistical) simulations, including ranges of uncertainty, were used to generate a low- and high-efficiency estimate, which results in estimation of a low and a high value of capacity. Capacity estimates produced using these methodologies are based on technically available capacities that have not been reduced by economic constraints, land use, or regulatory constraints. This assessment is a high-level overview and is not intended as a substitute for site-specific assessment and testing. Individual projects will require development of detailed geologic models and simulation of CO_2 injection to estimate capacity.

Oil and Gas Reservoirs

Oil and gas reservoir storage capacity was defined as volumes of the subsurface that have hosted natural accumulations of oil and/or gas and that could, in the future, be used to store CO_2. Mapping of the seal to oil and gas reservoirs is not required because the entrapment of hydrocarbons is considered evidence that a CO_2 containment seal is present and the associated water is assumed to be nonpotable. Minimum depth is assigned by each RCSP.

Two methods were used to estimate the CO_2 storage volume: (1) a volumetrics-based CO_2 storage estimate and (2) a production-based CO_2 storage estimate. The method selected by each RCSP was based on available data. No range of capacity values is proposed for oil and gas reservoirs, reflecting a relatively good understanding of volumetrics of this system. No distinction is made between reservoirs that are in production and those that are or will soon become mature or abandoned.

Unmineable Coal Seams

The absorptive nature of coal compared with that of porous media was expected to cause the range of parameters for displacement efficiency terms to be much higher than for porous media. Gas concentration from the Langmuir isotherm was substituted for the porosity that was used in other capacity calculations. It is assumed that delineation of most coals via mapping is better than quantification of porosity distribution in saline formations; however, some unmapped heterogeneity at a basin scale was included within the estimated value of the efficiency factor. The definition of unmineable coal varies from region to region due to depth distribution of the total resource relative to the rate and cost of mining.

The CO_2 storage efficiency factor has several components that reflect different physical barriers that inhibit CO_2 from contacting 100 percent of the coal bulk volume of a given basin or region. Depending on the definitions of area, thickness, and CO_2 concentration, the CO_2 storage efficiency factor may also reflect the volumetric difference between bulk volume and coal volume.

* Monte Carlo (statistical) simulations estimate a range for the efficiency factor between 28 and 40 percent; these values provide a 15–85 percent confidence range.

Saline Formations

A brine (saline) formation assessed for storage was defined as a porous and permeable body of rock containing water with total dissolved solids (TDS) greater than 10,000 mg/L, which has the capacity to store large volumes of CO_2. Capacities were determined for all saline formations below 2,500 ft where adequate data was available.

Assumptions used in the capacity estimate for saline formations include (1) saline formations are heterogeneous, (2) CO_2 storage will be under multiphase conditions, (3) only 20–80 percent of the area inventoried and 25–75 percent of the formation thickness assessed will be occupied by CO_2, and (4) the efficiency factor accounts for net to effective porosity, areal displacement efficiency, vertical displacement efficiency, gravity effects, and microscopic displacement efficiency.

Saline formations assessed for storage are restricted to those where the following basic criteria for the storage are met: (1) pressure and temperature conditions in the saline formation are adequate to keep the CO_2 in dense phase (supercritical) or liquid phase, (2) a suitable seal is present to limit vertical flow of the CO_2 to the surface, and (3) salinity in the saline formation is >10,000 ppm TDS. For this capacity estimate, a depth of 2,500 feet below surface is accepted as a reasonable proxy for these criteria to be met.
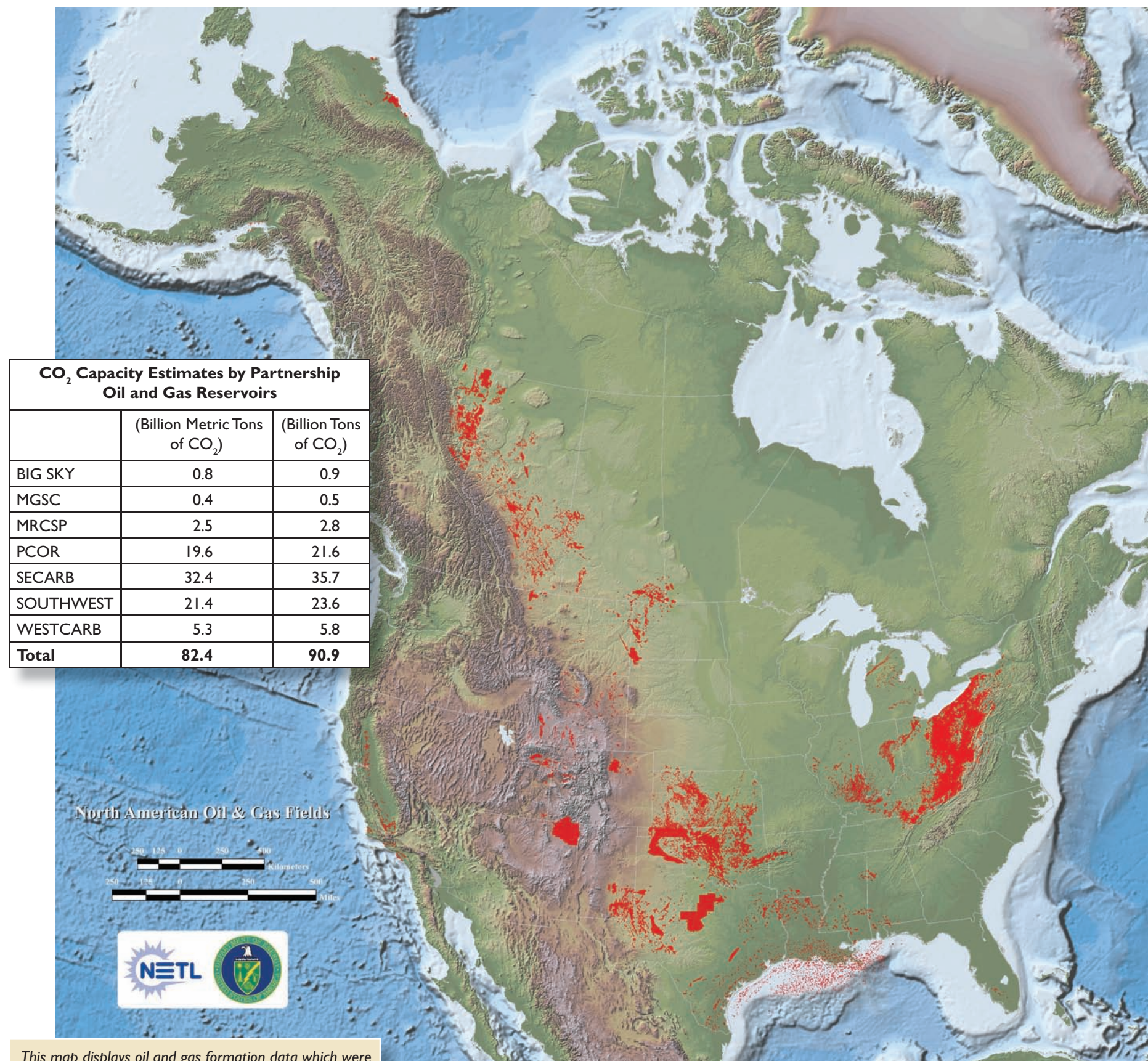
* Monte Carlo (statistical) simulations estimate a range for the efficiency factor between 1 and 4 percent of the bulk volume of saline formations for a 15–85 percent confidence range.

Oil and Gas Reservoirs

Mature oil and gas reservoirs have held crude oil and natural gas over millions of years. They consist of a layer of permeable rock with a layer of nonpermeable rock (caprock) above, such that the nonpermeable layer forms a trap that holds the hydrocarbons in place. Oil and gas fields have many characteristics that make them excellent target locations for geologic storage of CO_2. The geologic conditions that trap oil and gas are also the conditions that are conducive to CO_2 sequestration.

As a value-added benefit, CO_2 injected into a mature oil reservoir can enable incremental oil to be recovered. A small amount of CO_2 will dissolve in the oil, increasing the bulk volume and decreasing the viscosity, thereby facilitating flow to the wellbore. Typically, primary oil recovery and secondary recovery via a water flood produce 30-40 percent of a reservoir's original oil in place (OOIP). A CO_2 flood allows recovery of an additional 10-15 percent of the OOIP. NETL's work in this area is focused on increasing the amount of CO_2 that remains in the ground as part of CO_2 EOR injection.

While not all potential mature oil and gas reservoirs have been examined, the RCSPs have documented the location of more than 82.4 billion metric tons (90.8 billion tons) of sequestration potential in mature oil and gas reservoirs.
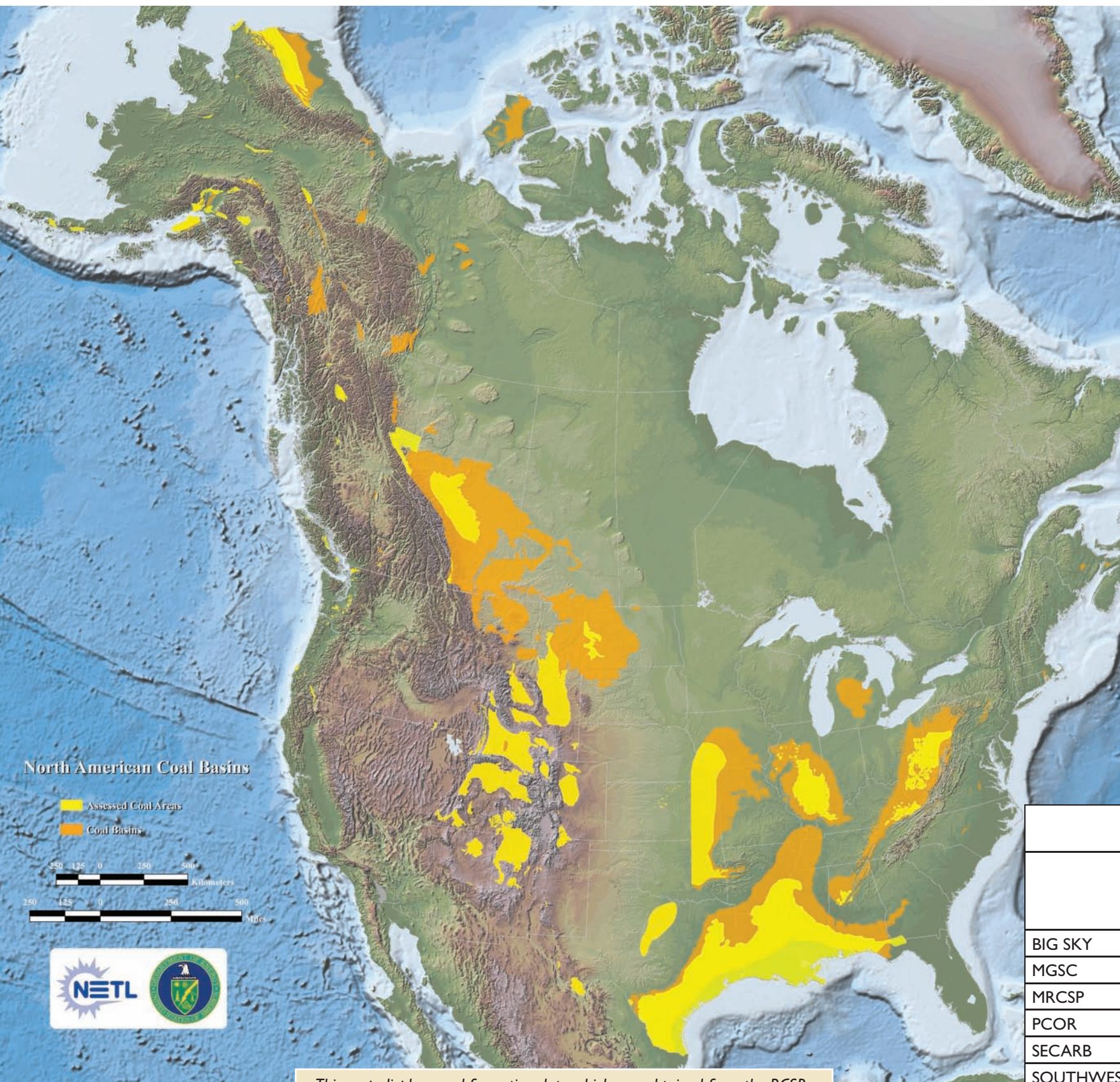
CO₂ Capacity Estimates by Partnership Oil and Gas Reservoirs		
	(Billion Metric Tons of CO_2)	(Billion Tons of CO_2)
BIG SKY	0.8	0.9
MGSC	0.4	0.5
MRCSP	2.5	2.8
PCOR	19.6	21.6
SECARB	32.4	35.7
SOUTHWEST	21.4	23.6
WESTCARB	5.3	5.8
Total	**82.4**	**90.9**

North American Oil & Gas Fields

NETL

This map displays oil and gas formation data which were obtained from the RCSPs and other external sources and compiled by NATCARB.

Unmineable Coal Seams

Unmineable coal seams are too deep or too thin to be economically mined. All coals have varying amounts of methane adsorbed onto pore surfaces, and wells can be drilled into unmineable coalbeds to recover this coalbed methane (CBM). Initial CBM recovery methods, such as dewatering and depressurization, leave a considerable amount of methane in the formation. Additional recovery can be achieved by sweeping the coalbed with CO_2. Depending on coal rank three to thirteen molecules of CO_2 are adsorbed for each molecule of methane released, thereby providing an excellent storage site for CO_2 along with the additional benefit of enhanced coalbed methane (ECBM) recovery. Similar to maturing oil reservoirs, unmineable coalbeds are good candidates for CO_2 storage.

While not all potential areas of unmineable coal have been examined, the RCSPs have documented the location of 156–183 billion metric tons (172–202 billion tons) of CO_2 sequestration potential in unmineable coal seams.

North American Coal Basins

Assessed Coal Areas
Coal Basins

250 125 0   250   500
                                Kilometers
250   125   0   250   500
                                  Miles

NETL

This map displays coal formation data which was obtained from the RCSPs and other external sources and compiled by NATCARB.
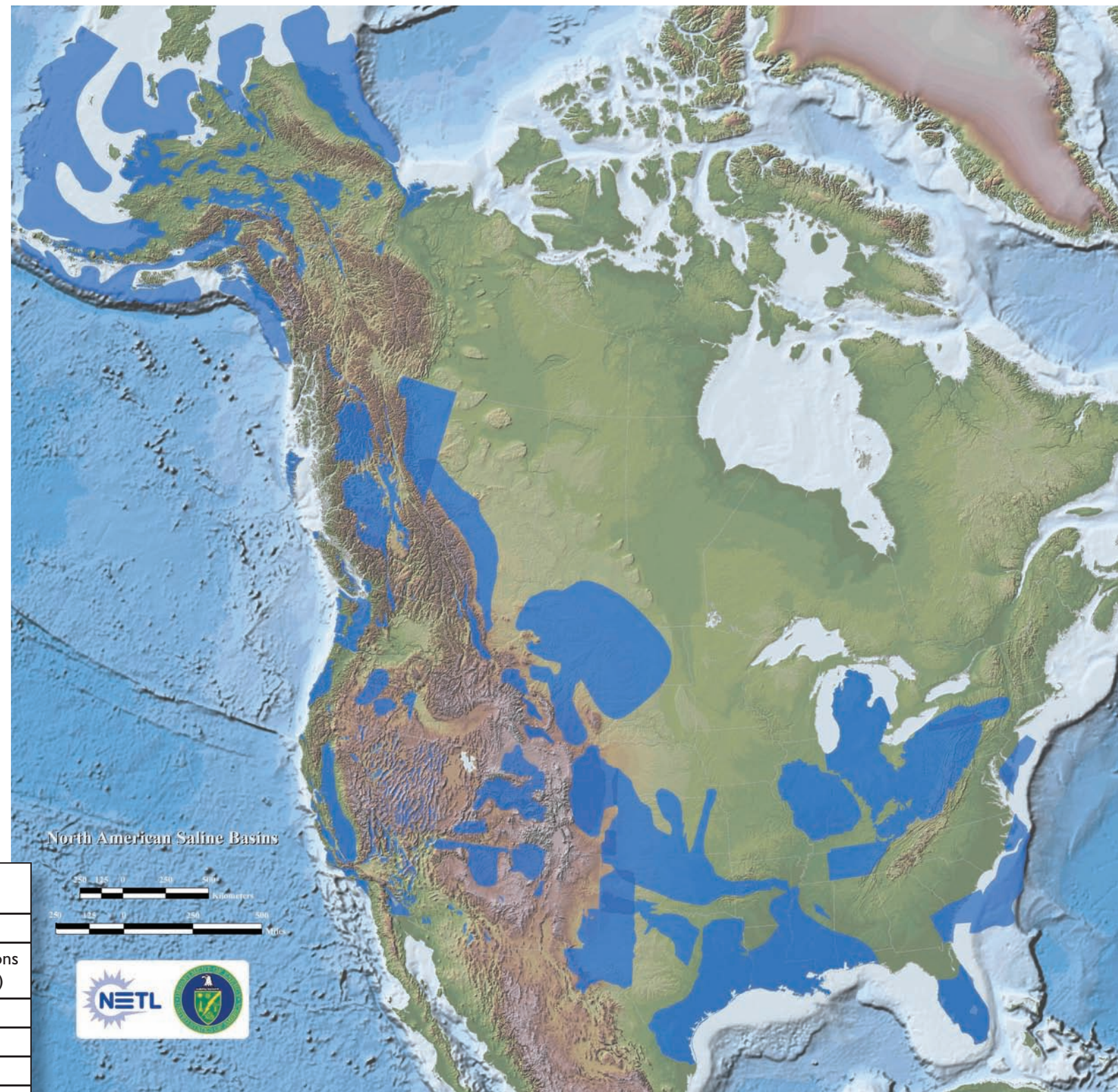
CO$_2$ Capacity Estimates by Partnership Unmineable Coal Seams				
	Low		High	
	(Billion Metric Tons of CO$_2$)	(Billion Tons of CO$_2$)	(Billion Metric Tons of CO$_2$)	(Billion Tons of CO$_2$)
BIG SKY	0.0	0.0	0.0	0.0
MGSC	2.3	2.5	3.3	3.6
MRCSP	0.7	0.8	1.0	1.1
PCOR	8.0	9.0	8.0	9.0
SECARB	57.4	63.3	82.1	90.5
SOUTHWEST	0.9	0.9	2.3	2.5
WESTCARB	86.8	96.1	86.8	96.1
Total	**156.1**	**172.6**	**183.5**	**202.8**

Deep Saline Formations

Saline formations are layers of porous rock that are saturated with brine. They are much more extensive than coal seams or oil- and gas-bearing rock, and represent an enormous potential for CO_2 storage. However, much less is known about saline formations because they lack the characterization experience that industry has acquired through resource recovery from oil and gas reservoirs and coal seams. Therefore, there is a greater amount of uncertainty regarding the suitability of saline formations for CO_2 storage.

While not all saline formations in the U.S have been examined, the RCSPs have documented the locations of such formations with an estimated sequestration potential ranging from 919 to more than 3,300 billion metric tons (from 1,014 to more than 3,700 billion tons) of CO_2.

North American Saline Basins

This map displays saline formation data which were obtained from the RCSPs and other external sources and compiled by NATCARB.

	CO_2 Capacity Estimates by Partnership **Saline Formations**			
	\multicolumn{2}{c}{Low}	\multicolumn{2}{c}{High}
	(Billion Metric Tons of CO_2)	(Billion Tons of CO_2)	(Billion Metric Tons of CO_2)	(Billion Tons of CO_2)
BIG SKY	271	299	1,085	1196
MGSC	29	32	115	127
MRCSP	47	52	189	208
PCOR	97	107	97	107
SECARB	360	397	1,440	1587
SOUTHWEST	18	20	64	71
WESTCARB	97	107	388	428
Total	**919**	**1,014**	**3,378**	**3,724**

This map displays basalt formation data which were obtained from the RCSPs and other external sources and compiled by NATCARB.
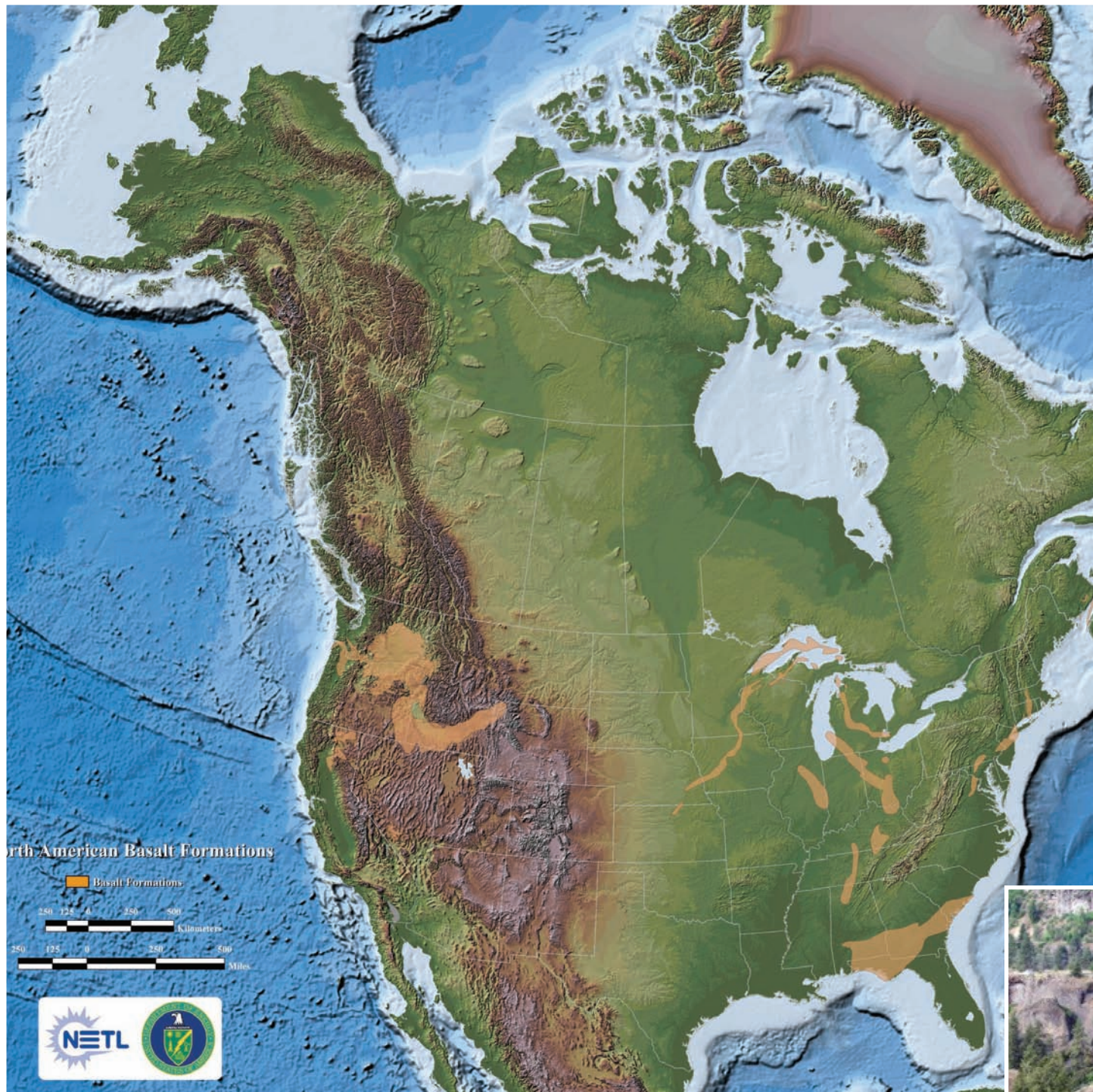
Future Geologic Sequestration Options

Other possible geologic sequestration options include basalts and shale formations.

Basalt Formations
Basalt formations are geologic formations of solidified lava. Basalt formations have a unique chemical makeup that could potentially convert all of the injected CO_2 to a solid mineral form, thus isolating it from the atmosphere permanently. Research is focused on enhancing and utilizing the mineralization reactions and increasing CO_2 flow within a basalt formation.
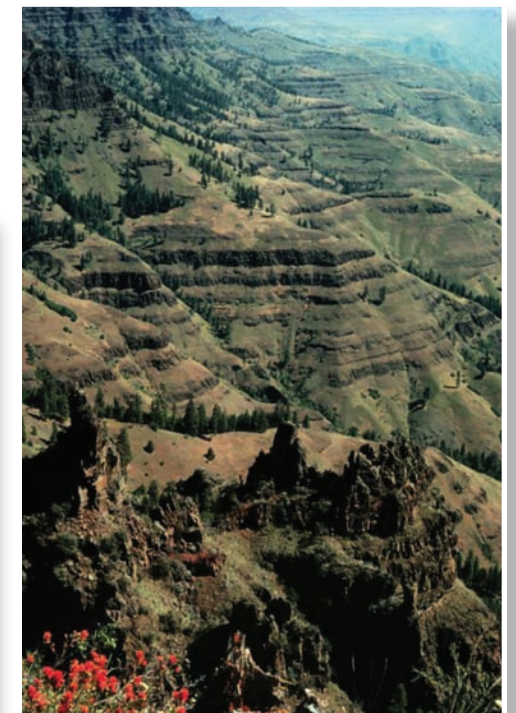
Organic Rich Shales
Shale, the most common type of sedimentary rock, is characterized by thin horizontal layers of rock with very low permeability in the vertical direction. Many shales contain 1–2 percent organic material in the form of hydrocarbons, which provides an adsorption substrate for CO_2 storage similar to CO_2 storage in coal seams. Research is focused on achieving economically viable CO_2 injection rates,

Basalt Formation

Columbia River Basalt

Terrestrial Sequestration

Terrestrial sequestration is CO_2 uptake by soils and plants, both on land and in aquatic environments such as wetlands and tidal marshes. Terrestrial sequestration provides an opportunity for low-cost CO_2 emissions offsets and usually offers additional benefits such as habitat or water quality improvements. Terrestrial efforts include tree-plantings, no-till farming, wetlands restoration, land management on grasslands and grazing lands, fire management efforts, and forest preservation. More advanced research includes the development of fast-growing trees and grasses and deciphering the genomes of carbon-storing soil microbes. NETL's Program efforts in the area of terrestrial sequestration include a focus on increasing carbon uptake on mined lands. These activities complement research into afforestation and agricultural practices that are being led by the U.S. Department of Agriculture (USDA). The U.S. DOE's Office of Science, U.S. EPA, and the Department of the Interior are also involved in terrestrial sequestration in supporting and complementary roles.

Afforestation on minelands provides more carbon sequestration per acre of land compared to grass planting. Tilling and soil amendment approaches provide a layer of loose earth that enables trees to take root. In some cases the tilled mineland is amended with coal combustion by-products to reduce its acidity. A layer of compacted earth is maintained under the loose earth to prevent rainwater from draining through the mine slag. These approaches can be applied to both closure practices at currently operating mines and reclamation of the nearly 6,070 km^2 (2,344 mi^2) of lands in the U.S. damaged by past mining practices.